FRACTURE ENERGY SPECIFICATIONS FOR MODIFIED ASPHALTS

Joseph E. Ponniah*
Ministry of Transportation, Ontario
1201 Wilson Avenue, Downsview, ON. M3M 1J8

Ralph A. Cullen and Simon A. Hesp*
Department of Chemistry, Queen's University
Kingston, ON. K7L 3N6

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INTRODUCTION

Low temperature cracking of asphalt pavements is a major performance problem in North America. In the past, extensive research has been done in this area to mitigate this problem. Recent findings by the Strategic Highway Research Program (SHRP) show that asphalt binder properties are by far the dominant factor controlling thermal cracking. Thus, the determination of these binder properties that affect thermal cracking is the key to the successful development of performance-based specifications for asphalt binders.

Traditionally, thermal cracking in asphalt pavements is controlled by using soft grades of asphalt cement based on penetration and viscosity measurements. Although, this approach has met with some success, it did not solve the problem completely. Besides, the emergence of modified asphalts has created a need for developing a suitable testing method for the characterization of binders containing additives. In general, asphalt pavement layers have built-in flaws (construction cracks). In addition, micro-cracks develop at the asphalt-aggregate interface due to differential thermal contraction of asphalt and mineral aggregates [1]. Micro-cracks can cause a localized stress concentration near discontinuities within the binder under thermally induced tensile loads. These stresses often reach a limiting value which leads to premature failures. Current binder specification limits do not consider the material resistance to these failure modes due to localized stress concentration. As a result, the actual performance often varies significantly from that anticipated by the design. What is required is a rational approach by which asphalt binders can be properly evaluated for their effectiveness to resist locally induced premature cracking.

There is some concern that the binder tests developed by SHRP may not be adequate to accurately predict the low temperature performance of modified asphalts. SHRP binder tests are mainly focussed on determining the creep stiffness or failure strains of asphalt binders at selected temperatures. Although these properties are necessary to globally characterize the low temperature behaviour of asphalt binders, they alone are not sufficient to reliably measure the resistance of asphalt binders to premature cracking. A complete knowledge of the damage process both at the micro and macro levels, is required to address the problem of premature fatigue cracking due to localized stress concentration, particularly in modified asphalts.

A review of the literature shows that fracture mechanics principles can be effectively used to control the fracture of materials which occur prematurely due to built-in flaws or cracks. The main objectives of this study are: a) to apply the fracture mechanics principles to characterize the low temperature fracture behaviour of asphalt binders; b) to develop a rational routine testing method using the fracture mechanics principles suitable for evaluating neat and modified asphalt binders with respect to low temperature cracking; (c) to analyze the correlation between the fracture properties and the low temperature performance.

SCOPE

The scope of the work includes: a) determination of binder properties and performance grade (PG) temperatures for the different asphalt binders using conventional and SHRP test methods; b) measurement of fracture properties (fracture toughness, fracture energy) of the asphalt binders selected in (a), using the newly developed fracture test method; c) determination of fracture temperatures of asphaltic concrete specimens containing the same binders as in (a) and (b), using the Thermal Stress Restrained Specimen Test (TSRST); and d) establishment of a correlation among the binder properties (determined from SHRP tests and the fracture test method) and the mix fracture temperature.

* To whom the correspondence may be addressed

APPLICATION OF FRACTURE MECHANICS PRINCIPLES

Fracture mechanics is a technique which identifies the cause of premature failure of materials due to built-in flaws, such as micro-cracks, under a load much smaller than the design load. If the material is homogeneous and behaves in a linear elastic manner, the effect of stress concentration around a micro-crack can be measured in terms of a parameter, called stress intensity factor (K_I). K_I increases with an increase in the external load and when it reaches a critical value, K_{Ic}, unstable fracture occurs. The parameter, K_{Ic}, called the fracture toughness, decreases with an increase in specimen thickness reaching a constant minimum value when plane-strain conditions are reached. This lower level of K_{Ic} is reproducible and can be used as a material property to evaluate the brittle fracture of materials in the same manner as the yield strength is used for structural analyses. This means that the fracture toughness can also be used to study the brittle fracture behaviour of asphalt binders at low temperatures. However, when polymers are added to the asphalt, the modified binder exhibits different failure behaviour at low temperatures, ranging from brittle fracture to plastic deformation or excessive elongation. This is because the modified asphalts usually contain finely dispersed secondary phases within the polymer matrix which contribute to shear yielding mechanisms and thereby prevent brittle failure. Fracture mechanics suggests that, when a material undergoes yielding (creep), it is the rate of energy dissipation (fracture energy) which controls the failure mode from crack initiation to full depth crack propagation. As explained later, fracture energy can be calculated once the fracture toughness and the stiffness modulus values are obtained. Thus, it appears that fracture energy will give valuable and consistent information on the effectiveness of modifiers in increasing the fracture resistance of asphalt binders. The question still remains how effective the fracture energy specification is as compared to the SHRP binder specification with respect to low temperature cracking. An experimental investigation was carried out to compare the correlation between the low temperature performance and the binder properties determined from the fracture test and those from SHRP tests. As well, trial sections were installed in Northern Ontario to compare the findings of the laboratory investigation with the long term low temperature performance of the modified asphalts in the field.

EXPERIMENTAL INVESTIGATION

Materials

Two types of conventional asphalts (85-100 pen and 150-200 pen) and five different modified asphalts were used in the experimental program. These modified asphalts were specifically selected or designed in such a way to give a wide range of performance levels. For this purpose, different modifiers and various grades of base asphalts, ranging from hard (85-100 pen) to soft (300-400 pen) asphalts were used in this study. As such, the performance of different modifiers will not be addressed. The suppliers who participated in this study include: Petro Canada, Huskey Oil, Bitumar, Polyphalt, and McAsphalt.

TESTING PROCEDURES

Thermal Stress Restrained Specimen Test (TSRST)

The Thermal Stress Restrained Specimen test is intended to simulate conditions that a mix would experience in the field. The test specimens of approximately 100x35x35 mm size were made from asphaltic concrete briquettes prepared using the plant mix from the trial sections. Each specimen was glued to the end plates of a test frame located within a temperature controlled chamber. The specimen was restrained by the end plates while the temperature in the chamber was gradually reduced at -10°C/ hour until the specimen failed due to thermally induced stresses. However, the potential change in specimen length due to the thermal shrinkage was compensated by the computer software system which was linked to two linear variable displacement transducers (LVDT) placed in between the end plates. The software uses the signals from the transducers to maintain a constant specimen length during testing. The output gives the temperature and the stress within the material at failure. The measured specimen failure temperature due to low temperature shrinkage is a good performance indicator of different binders used in the specimens.

Table 1: TSRST Results

Binder	Failure Stress (MPa)	Failure Temp (C)
Control 150-200	not tested	not tested
Control 85-100	2.24	-25.7±5.7
A	2.83	-45.4±2.5
B	2.65	-42.8±2.5
C	2.15	-42.9±4.9
D	8.31	-34.4±7.5
E	1.92	-29.5±8.1

A summary of the results together with 90% confidence intervals is presented in Table 1. The results indicate that binder A, with an average failure temperature of -45.4° C, will perform better than the rest, closely followed by binders C and B. The binder which has the lowest resistance to low temperature cracking, as expected, is the 85-100 pen asphalt. This test is time consuming and cannot be used on a routine basis; but it is a valuable research tool for investigating the low temperature performance of asphalt pavements

FRACTURE ENERGY TEST

Fracture energy testing was carried out by using a three point bending beam method (Figure 1) based on ASTM E 399-90 procedures [2]. The neat and modified binder beam samples were prepared using 25 mm wide by 12.5 mm deep by 175 mm long silicone rubber molds which have 90° starter notches, 5 mm deep, at the centre of the bottom surface. The molds were filled with asphalt binders and kept in a freezer at -20 °C for about two hours until they became solidified. The binder samples were then removed from the molds and were kept at the testing temperature for 18 hours. The starter notch in each sample was sharpened with a razor blade prior to testing. The notched beam is then placed on a three point bending apparatus of span 100 mm within an environmentally controlled chamber (Figure 1). The beam was then loaded until failure. From the output, the fracture toughness was computed according to Equation (1).

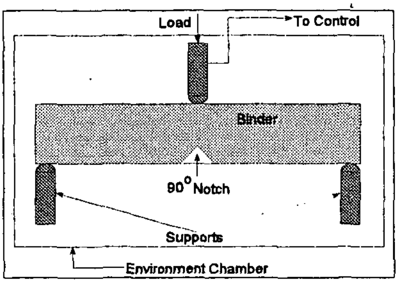

Figure 1: Fracture Toughness Apparatus

$$K_{IC}=\frac{PS}{BW^{3/2}}\left[\frac{3\left(\frac{a}{W}\right)^{1/2}\left[1.99-\frac{a}{W}\left(1-\frac{a}{W}\right)\left(2.15-3.93\frac{a}{W}+2.7\frac{a^2}{W^2}\right)\right]}{2\left(1-2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}\right] \quad (1)$$

Where: K_{IC} is the fracture toughness; P is the failure load; S is the span; B is the specimen depth; W is the specimen width; a, is the crack length.

The fracture energy can then be derived from:

$$G_{IC}=\frac{K_{IC}^2(1-v^2)}{E} \quad (2)$$

Where: G_{IC} is the fracture energy (Jm^{-2}); ν is Poisson's ratio; E is Young's Modulus. As Poisson's ratio for asphalt cement at low temperature is very small, it is neglected in the computation of G_{IC} using Equation 2. A couple of tests were carried out to ensure plane-strain conditions as discussed previously so that the fracture toughness values remain constant and reproducible. Secondly, the linear-elastic behaviour of the specimens was achieved by selecting the appropriate low test temperatures. For modified samples, the test temperature was -30 °C and the results are given in Table 2. Fracture toughness values in this table provide information on the type and amount of polymers used while the modulus gives information on the type of base asphalts used. Fracture energy measures the resistance of the binder to fracture. The results show that binder A has a higher resistance to thermal cracking than the rest, followed by binders C and B. The results also show that binder D, which used a harder base asphalt (85-100 pen), gives lower fracture energy while the binders A, B, and C used a softer base asphalt (150-200 pen) to give higher energy values. This supports the common believe that modified binder with a soft base asphalt is most suitable for preventing low temperature cracking.

Table 2. Fracture Energy Test Results at -30°C

Binder	Fracture Toughness ($kNm^{-3/2}$)	Modulus (Mpa)	Fracture Energy (Jm^{-2})
150/200 pen	*	*	*
85/100 pen	*	*	*
A	63.4	0.79	5.1
B	57.0	0.78	4.2
C	57.3	0.73	4.5
D	70.1	1.66	3.0
E	48.4	0.83	2.8

* Samples were too brittle and failed immediately

Figure 2 shows an obvious link between fracture energy and the low temperature TSRST performance. The regression analysis gives a strong correlation coefficient R^2 of 0.933. The good correlation implies that fracture energy can be used to develop a low temperature performance-based specification.

SHRP BINDER TESTS

SHRP binder tests were carried out using the control and modified samples. Table 3 provides the SHRP performance grades (PG) of the conventional asphalts and those of binders A, B, C, D, and E. Figure 3 shows the weak correlation between the PG grade values and the fracture temperatures with an R^2 value of 0.672. Alternatively, the relationship between the binder creep stiffness and fracture temperature was also investigated as shown in Figure 4. There is some improvement in the R^2 value but the correlation is still not as good as for that of G_{IC}. When the results of the SHRP direct tension test were compared with the fracture temperature it gave a very poor correlation (R^2 value = 0.004) as shown in Figure 5.

Table 3: SHRP low temperature performance grade results

Binder	Performance Grade (°C)
Control 150-200	-24
Control 85-100	-20
A	-32
B	-28
C	-26
D	-21
E	-26

PENETRATION TEST

Penetration tests were performed at 25° C after aging the binder using the Rolling Thin Film Oven Test method. Figure 5 shows that the correlation between the penetration values and the fracture temperatures is even better than that observed for the SHRP binder test results. This seems to indicate that SHRP binder testing system has not improved the existing characterization system with regards to modified binders

4.0 CONCLUSIONS

- Fracture energy shows the best correlation (R^2 =0.933) with TSRST failure temperatures .
- Because of the high correlation and the fact that it is a fundamental material property, fracture energy seems to offer promise for use in the development of a low temperature performance-based specification for modified binders.
- The SHRP approach to establish a low temperature performance grade for asphalts based on binder creep stiffness, m-value, and failure strain gives a poor correlation with the TSRST failure temperatures
- The correlation between the penetration test results and the performance is comparable to that observed for the SHRP binder tests. However, the results are not conclusive because of the limited data.

Table 4: Penetration Test Results

Binder	Aged Pen 25° C
Control 150-200	85
Control 85-100	47
A	87
B	65
C	66
D	41
E	39

5.0 RECOMMENDATIONS

- Expand the study so that the effects of aging on fracture toughness / fracture energy properties can be determined
- Establish a set of critical fracture energies so that low temperature Performance Grades can be established using fracture energy testing.
- Relate the experimental data to the field observation from the Hwy 118 test sections in Northern Ontario. This should be done to verify if experimental predictions can be related to actual field performance.

6.0 REFERENCES

1. El Hussein H. Mohamed, Kwang W. Kim, and Joseph Ponniah, "Assessment of Localized Damage Associated with Exposure to Extreme Low Temperatures", Transportation Research Board, Washington, D. C., January, 1996.
2. ASTM Method E 399-90 (1984) Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials. Philadelphia: ASTM.

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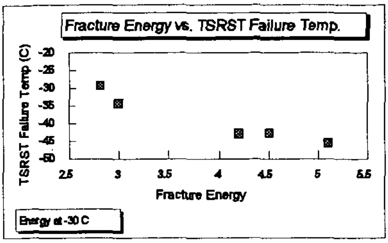
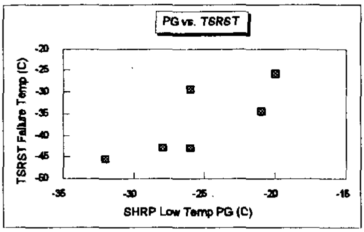


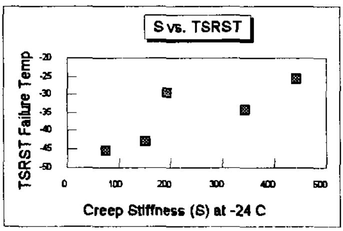
R^2= 0.933

Figure 2: Fracture Energy vs TSRST Failure Temperature



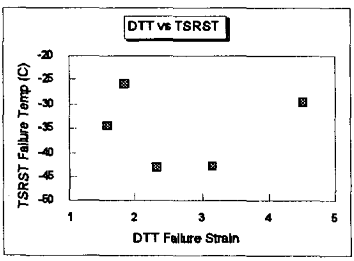
R^2= 0.617

Figure 3: *Performance Grade vs TSRST Failure Temperature*



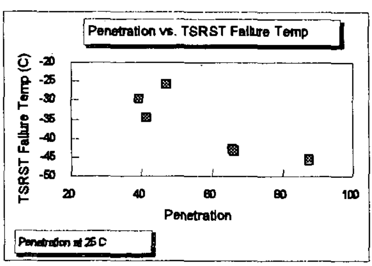
R^2= 0.672

Figure 4: Creep Stiffness vs Failure Temperature



R^2= 0.0004

Figure 5: Failure Strain vs TSRST Failure Temperature



R^2= 0.702

Figure 6: Correlation for Aged Binder at 25°C